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**DETERMINING CRITERIA FOR
SINGLE STAGE TO ORBIT**

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INTRODUCTION

The following exercise will determine the criteria for Single Stage to Orbit booster vehicles. To validate the assumptions and results several existing vehicles are examined. As a control the Manned Space Shuttle is used to calculate the equivalent orbital velocity. This velocity is then used to determine if the selected vehicle can achieve orbit and to calculate its payload capacity.

The following vehicles were chosen to determine if they could achieve orbital velocity in a single stage:

Saturn V

Second Stage (SII) w/SSME engines
Second Stage (SII) w/J2 engines
Third Stage (S4B) w/SSME engines
Third Stage (S4B) w/J2 engines

Space Shuttle

External Tank w/SSME engines
External Tank w/J2 engines

Atlas Rocket Booster(current configuration)

Note: The Space Shuttle's External Tank will be configured as a "Stage and a Half" Rocket Booster. This is accomplished by placing liquid fueled engines under its aft fuel dome. A payload pod, without engines, will be mounted in the location usually reserved for the Orbiter.

Performance is sacrificed to achieve single stage to orbit. Additional calculations will be performed using the SSME-External Tank vehicle. In this concept the vehicle will stage unneeded propulsion capability at an appropriate staging velocity. This vehicle is given the name (1.5) External Tanker - SSME. It is comprised of a Booster Unit (liquid fueled engines and vehicle support structure) mounted on the aft end of the External Tank assembly. At staging velocity, the booster engines and vehicle support structure are jettisoned while the remaining engines and vehicle continues on to orbit, similar to the Atlas Rocket Booster.

(1.5) EXTERNAL TANK-SSME EVALUATION Staged Booster Unit

A propulsion evaluation was performed for the (1.5) External Tank - SSME Vehicle using parameters from SRB-STS (see Appendix A and B). Gross Lift-Off Weight (GLOW) was calculated as 1844.2 Klbs. The total Vehicle Dry Weight at Launch was calculated as 254,060 lbs. Of this dry weight 84,240 lbs will be usable payload.

EXISTING VEHICLE EVALUATION

Single Stage to Orbit

A propulsion evaluation was performed for each of the existing vehicles listed below (Single Stage to Orbit configuration) using parameters from SRB-STS (see Appendix A, C, and D). All SII and all External Tank vehicle configurations could achieve orbit with a useful payload. The best configuration, the Space Shuttle's External Tank with SSME engines, could achieve orbital velocity with 52,800 lbs of usable payload.

Saturn V

Second Stage (SII) w/SSME engines
Second Stage (SII) w/J2 engines
Third Stage (S4B) w/SSME engines
Third Stage (S4B) w/J2 engines

Space Shuttle

External Tank w/SSME engines
External Tank w/J2 engines

Atlas Rocket Booster(current configuration)

CONCLUSION

A substantial schedule and manpower savings could be realized if a Single Stage to Orbit vehicle could be produced. Several configurations were studied using existing hardware. A relationship was obtained to determine if a configuration could obtain orbital velocity. This dimensionless relationship was given by the following:

$$\text{GAMMA\%} = (\text{Non Payload} / \text{Gross Lift-Off Weight})\% * \\ \exp(\text{Alpha}/\text{Isp})$$

where Isp is the average Specific Impulse of the liquid rocket engine during the entire boost phase. Alpha, a dimensionless value which is a function of trajectory and inflight losses, was determined to be 954.65 in this exercise using only rough order magnitude assumptions. Orbital velocity is obtained in a single stage for GAMMA% less than 100%. This relationship can be applied to any vehicle, including NASP.

Since performance is sacrificed to achieve single stage to orbit, additional calculations were performed using one of the configurations as a one & one half stage vehicle. The one & one half stage vehicle offered a 59.6% increase in useful payload to orbit while the Single-Stage to Orbit vehicle would offer a reduced manpower and schedule requirements.

APPENDIX A

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To find an unknown propulsion parameter of a vehicle the following calculations are made:

$$\text{EQU 1.) } V_b = G * I_{sp} * \ln(M_{ini} / M_{fin}) - k * G * t$$

where

V_b = Velocity of vehicle after fuel has been expended
 G = Gravitational constant = 32 feet per sec per sec
 I_{sp} = Specific Impulse of total vehicle (lbf / lbm/sec)
 M_{ini} = Mass of initial vehicle
 M_{fin} = Mass of vehicle after fuel has been expended
 t = Amount of time to achieve V_b after lift-off
 k = Correction Factor - derived by considering the amount of time thrust is used to overcome gravity.

The following known characteristics from Solid Rocket Booster - Shuttle (SRB-STS) will be used to find unknown characteristics of the Single Stage to Orbit vehicles.

TABLE 1

Solid Rocket Booster = Shuttle (SRB-STS) Parameters

220,092 lbs	Orbiter Inert & OMS Propellant
51,246 lbs	Usable Payload
66,760 lbs	External Tank
376,416 lbs	SRB (dry weight) * 2
<hr/>	
714,514 lbs	Total Vehicle Dry Weight @ Launch
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338,098 lbs	Mass at Main Engine Cut-Off (MECO)
1,590,128 lbs	External Tank Fuel
4,525,000 lbs	Gross Lift-Off Weight (GLOW)
1,542,000 lbs	Mass after Booster Separation
269 (228) Sec	Booster Isp in Vacuum (Sea/Level)
2,397,000 lbs	Average Booster Thrust (Boost Phase)
123.6 Seconds	Time to Booster Separation
<hr/>	
<u>Rocketdyne SSME Parameters</u>	
453.5 (361)[407]Sec	SSME Isp in Vacuum (S/L) [Ave Boost Phase]
471(377)[424]Klb	SSME Thrust in Vacuum (S/L) [Ave Boost Phase]
6986 lbs	SSME Weight
67.4 lbf/lbm	SSME Thrust to Weight
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<u>Rocketdyne J2 Parameters</u>	
427 (341.6)[384]Sec	J2 Isp in Vacuum (S/L) [Ave Boost Phase]
230(184)[207]Klb	J2 Thrust in Vacuum (S/L) [Ave Boost Phase]
3480 lbs	J2 Weight
66.1 lbf/lbm	J2 Thrust to Weight

Average Thrust and Average Specific Impulse was derived by assuming the vehicle was reacting against a degrading air pressure during boost phase.

APPENDIX A

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STS-SRB EVALUATION

Using Equation 1) a propulsion analysis of today's SRB-STS will reveal parameters which can be correlated with the Supertanker. The velocity gained by the SRB-STS after Booster Separation is calculated by the following:

Using Eq 1):

$$V_{meco} = (32 \text{ ft/sec}^2) * 453.5 \text{ Sec} * \ln(1542/338) - 0 \\ = 22,026 \text{ Ft/sec}$$

It was assumed that "k" was zero in the above equation to give a Rough Order of Magnitude value. When the above result is correlated with the Supertanker, this parameter nearly cancels out.

Because the Specific Impulse is different for the SSME's and the SRB, the Average Vehicle Isp during the boost phase is calculated by doing the following:

EQU 2) Average Vehicle Isp =
$$\{(Isp_1 * Thrust_1) + (Isp_2 * Thrust_2)\} / (Thrust_1 + Thrust_2)$$

Ave Veh Isp = 310.3 Seconds from the calculation
$$\{(407\text{sec} * 1272\text{Klb}) + (259\text{sec} * 2397\text{Klbs})\} / (1272\text{Klbs} + 2397\text{Klbs})$$

Using Eq 1):

$$V_{boost.sep} = (32 \text{ ft/sec}^2) * 310.3 \text{ Sec} * \ln(4525/1542 + 376) - \\ 0.9 * 32 \text{ ft/sec}^2 * 123.6 \text{ Sec}$$

Velocity at Booster Separation = 4,963 Ft/sec or Mach 4.67

"k" was assumed to be 0.9 after reviewing the flight trajectory until booster separation at 23 miles downrange and 29 miles altitude, and realizing that 90% of this boost energy was spent overcoming gravity.

Total Velocity Gained by the vehicle after launch:
22,026 Ft/sec + 4,963 Ft/sec = 26,989 FT/sec

Total Delta V at MECO = 30,550 Ft/sec

(1.5) EXTERNAL TANK-SSME EVALUATION
Staged Booster Unit

Using Equation 1) a propulsion analysis of the ET-SSME Vehicle (with stage Booster Unit) will reveal its propulsion parameters. The payload capacity of the ET-SSME Vehicle is calculated by the following:

It will be assumed for ease of calculations this vehicle will have the same performance characteristics (Staging Velocities, Thrust-to-Weight, "k" values) as the SRB-Shuttle. Also, specifics in performance of an operational vehicle (i.e., unused fuel, safety margins, increased mass of possible larger LOX feedline, primer on every other fastener) will be assumed to be included in this Rough Order of Magnitude exercise.

Using Eq 1):

$$22,026 \text{ Ft/sec} = (32 \text{ ft/sec}^2) * 453.5 \text{ Sec} * \ln(M_{sep} - M_{jet} / M_{orb}) - 0$$

result 1] $M_{sep} = 4.562 M_{orb} + M_{jet}$

The mass jettisoned (M_{jet}) at staging velocities is comprised of 4 booster engines and half of the booster unit structure mass. This would leave 3 retained SSME's and half of the booster unit structure mass to travel on to orbit.

$$\begin{aligned} M_{jet} &= M(4 \text{ Boost.Eng}) + 0.5 * M_{boost.\text{Unit Struct}} \\ M_{jet} &= 28,000 \text{ lbs} + 16,500 \text{ lbs} = 44,500 \text{ lbs} \end{aligned}$$

result 2] $M_{sep} = 4.562 M_{orb} + 44,500 \text{ lbs}$

The same vehicle performance as found for SRB-Shuttle is assumed for this vehicle therefore, the following calculation is performed to find the relation of Gross Lift-Off Weight and the mass of the vehicle after Booster Unit Separation (M_{sep}):

Using Eq 1):

$$\begin{aligned} 4,963 \text{ Ft/sec} &= (32 \text{ ft/sec}^2) * 435.5 \text{ Sec} * \ln(GLOW/M_{sep}) \\ &\quad - 0.9 * 32 \text{ ft/sec}^2 * 123.6 \text{ Sec} \end{aligned}$$

result 3] $1.843 M_{sep} = GLOW$

combining result 2] and result 3] to yield Mass to Orbit (M_{orb}) in terms of GLOW

$$\begin{aligned} 1.843 (4.562 M_{orb} + 44,500) &= GLOW \\ \text{result 4]} \quad 8.409 M_{orb} + 82,000 \text{ lbs} &= GLOW \end{aligned}$$

APPENDIX B

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**(1.5) EXTERNAL TANK-SSME EVALUATION
Staged Booster Unit**

A breakdown of the Gross Lift-Off Weight (GLOW) will yield another relationship for GLOW and Morb.

TABLE 2

Gross Lift-Off Weight (GLOW)

Mass Jettisoned	44,500 lbs
Mass to Orbit	Morb (unknown)
GLOW =	1,634,628 lbs + Morb

GLOW values are substituted into result 4] to find the Mass of vehicle that achieves orbital velocity.

$$8.409 \text{ Morb} + 82,000 \text{ lbs} = 1,634,628 \text{ lbs} + \text{Morb}$$

result 5] Morb = 209,560 lbs

A breakdown of the Mass to Orbit (Morb) will finally yield the amount of usable payload to 100 mile orbit at 28.5 degree.

TABLE 3

Mass to Orbit (Morb)

External Tank Mass	66,760 lbs
Booster Engines * 3	21,000 lbs
50% Booster Unit Structure	16,500 lbs
Mass Payload Pod	21,060 lbs
Usable Payload	84,240 lbs

Note: Mass of Payload Pod was assumed as 1/4 of usable payload.

Mass to Orbit	218,560 lbs
Vehicle Dry Weight @ Launch	329,765 lbs
Gross Lift-Off Weight	1,844,190 lbs
Dry Launch Mass to GLOW fraction	0.1378
Payload to GLOW fraction	0.0457

APPENDIX C

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EXTERNAL TANK-SSME VEHICLE EVALUATION
(SINGLE STAGE TO ORBIT)

Using Equation 1) a propulsion analysis of the ET-SSME Vehicle will reveal its propulsion parameters. The payload capacity of the ET-SSME Vehicle with Single-Stage-To-Orbit trajectory is calculated by the following:

Since the vehicle is a Single-Stage-To-Orbit, the mass to orbit will be simply the inert mass at launch. This mass to orbit can be calculated by one iteration of Equation 1) with using the Total Velocity Gained by the SRB-STS vehicle found above. Only 6 SSME's will be used instead of 7. It is assumed the lower thrust to weight at liftoff (calculated below) for the ET-SSME will be balanced by its quicker orbital insertion.

Using Eq 1):

$$26,989 \text{ Ft/sec} = (32 \text{ ft/sec}^2) * 441.2 \text{ Sec} * \ln (\text{Fuel} + \text{Morb/Morb}) -$$

$$0.9 * 32 \text{ ft/sec}^2 * 123.6 \text{ Sec}$$

or

Equation 3): $\text{Morb} = \text{Fuel} / \{\exp(954.65/\text{Isp})\} - 1\}$

$$\text{Mass to Orbit} = 206,387 \text{ lbs}$$

GLOW would then simply be $206,387 + 1,590,128 \text{ lbs}$ or $1,796,515 \text{ lbs}$.

NOTE: The given Isp has been averaged over the entire burn until orbit.

A breakdown of the Mass to Orbit (Morb) will finally yield the amount of usable payload to 100 mile orbit at 28.5 degree.

TABLE 5
Mass to Orbit (Morb)

External Tank Mass	66,760 lbs
Booster Unit (six-engines)	41,916 lbs
Booster Unit (Structure)	32,396 lbs
Mass Payload Pod	13,063 lbs
Usable Payload	52,252 lbs
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Total Vehicle Dry Weight @ Launch	206,387 lbs

Note: Mass of Payload Pod was assumed as 1/4 of usable payload.

Mass to Orbit	206,387 lbs
External Tank Fuel	1,590,128 lbs
Gross Lift-Off Weight	1,796,515 lbs
Dry Launch Mass to GLOW fraction	0.1149
Payload to GLOW fraction	0.0291

APPENDIX D
EXISTING VEHICLE EVALUATION
(SINGLE STAGE TO ORBIT)

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Using Equation 2) a propulsion analysis of existing vehicles using different engine performance will reveal their propulsion parameters. The payload capacity of each selected vehicle is calculated using equation 2) and assuming the trajectory will remain the same for the given thrust to weight at lift-off.

TABLE 6

<u>VEHICLE</u>	TANK DRY <u>WT (LBS)</u>	TANK FUEL	MASS TO <u>ORBIT</u> ¹	Bstr.Unt ³ <u>Structure</u>	PL POD ⁴ <u>Fairing</u>	Usable <u>Payload</u>	Non-P/L <u>Dry Mas</u>
ET-SSME	66,760	1,590,128	206,180	31,400	13,000	52,800	153,380
ET-J2	66,760	1,590,128	178,220	31,000	7,740	30,960	147,260
SII-SSME	78,750	992,700	128,700	N/A	3,920	15,680	109,100
SII-J2	78,750	992,700	111,260	N/A	1,165	4,660	106,600
S4B-SSME	24,900	238,175	30,880 ²	N/A	0	0	31,900 ⁵
S4B-J2	24,900	238,175	26,700 ²	N/A	0	0	31,860 ⁵
ALTAS-STO	5,420	303,200	8,579 ²	N/A	0	0	9,595 ⁵

NOTE 1: 100 mile orbit at 28.5 degree direct insertion

NOTE 2: Mass to orbit was not greater than Inert Weight of vehicle. Orbital velocity was not achieved.

NOTE 3: Booster Unit Structure is calculated as 1.75% of GLOW for External Tank vehicles. For External Tank vehicles this structure includes the weight of avionics, manifolds, and TVC's. The Saturn Vehicles are already designed to be supported from the aft end and Booster Unit Structure Mass is included with dry tank weight.

NOTE 4: Payload Pod is calculated as one-fourth of usable payload

NOTE 5: Hypothetical weight of vehicle with no payload.

APPENDIX D
EXISTING VEHICLE EVALUATION
(SINGLE STAGE TO ORBIT)

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<u>VEHICLE</u>	<u># OF ENGINES</u>	<u>ENGINE</u>	<u>THRUST TO WT</u>	TABLE 7			<u>Payload to GLOW%</u>	<u>Gamma%⁶</u>
				<u>Avg</u>	<u>Non P/L</u>	<u>TO GLOW%</u>		
ET-SSME	6	42,000	1.259	441	8.539%	2.929%	74.39	
ET-J2	12	41,760	1.250	416	8.328%	1.751%	82.64	
SII-SSME	4	27,950	1.345	441	9.729%	1.340%	84.76	
SII-J2	8	27,850	1.250	416	9.656%	0.422%	95.81	
S4B-SSME	1	7,000	1.409	441	11.856%	0.000%	103.29	
S4B-J2	2	6,960	1.258	416	12.028%	0.000%	119.35	
ATLAS-ST0	3	4,175	1.400	266	3.068%	0.000%	111.48	

NOTE 6: GAMMA% is calculated by the following:

Equation 4) $\text{GAMMA\%} = (\text{Non Payload} / \text{GLOW})\% * \exp(954.65/\text{Isp})$

When GAMMA% is greater than 100% then, there can be no useful payload to orbit.

The latter term in equation 4) is 8.7123 for SSME's and 9.9228 for J2's.

ATTACHMENT TO "DETERMINING CRITERIA FOR SINGLE SINGLE STAGE TO ORBIT"
30 October 1990

SINGLE SINGLE STAGE TO ORBIT
RATIONALE

An all LOX/LH₂ Liquid Rocket Booster Space Shuttle has been proposed by a contractor (Reference 1). In this concept two 16.16 foot diameter boosters would replace the current solid rocket boosters. Each of these boosters had a LOX tank forward of the LH₂ tank and was propelled by four - 565,000 lb thrust engines.

A recent study was completed which placed these same eight booster engines under a single LOX/LH₂ tank (Reference 2). This tank was enlarged in diameter to contained the extra propellant for both the booster engines and Space Shuttle Main Engines. This vehicle, given the name "Supertanker", would jettison the booster engines and associated propulsion hardware at staging velocity.

If this jettisoned hardware was retained until orbital velocity is achieved (Single-Stage-To-Orbit), useful payload would be sacrificed for greater Launch Operations Efficiency (Reference 3). However, payload capacity greatly increases if vehicle performance is optimized within the bounds of Launch Operation Efficiency.

Note: The source mistakenly used a heavy weight External Tank Mass in their original design work instead of the Light Weight Tank Mass (Reference 3). This weight savings was transferred to payload capacity for the LOX/LH₂ LRB Shuttle.

References

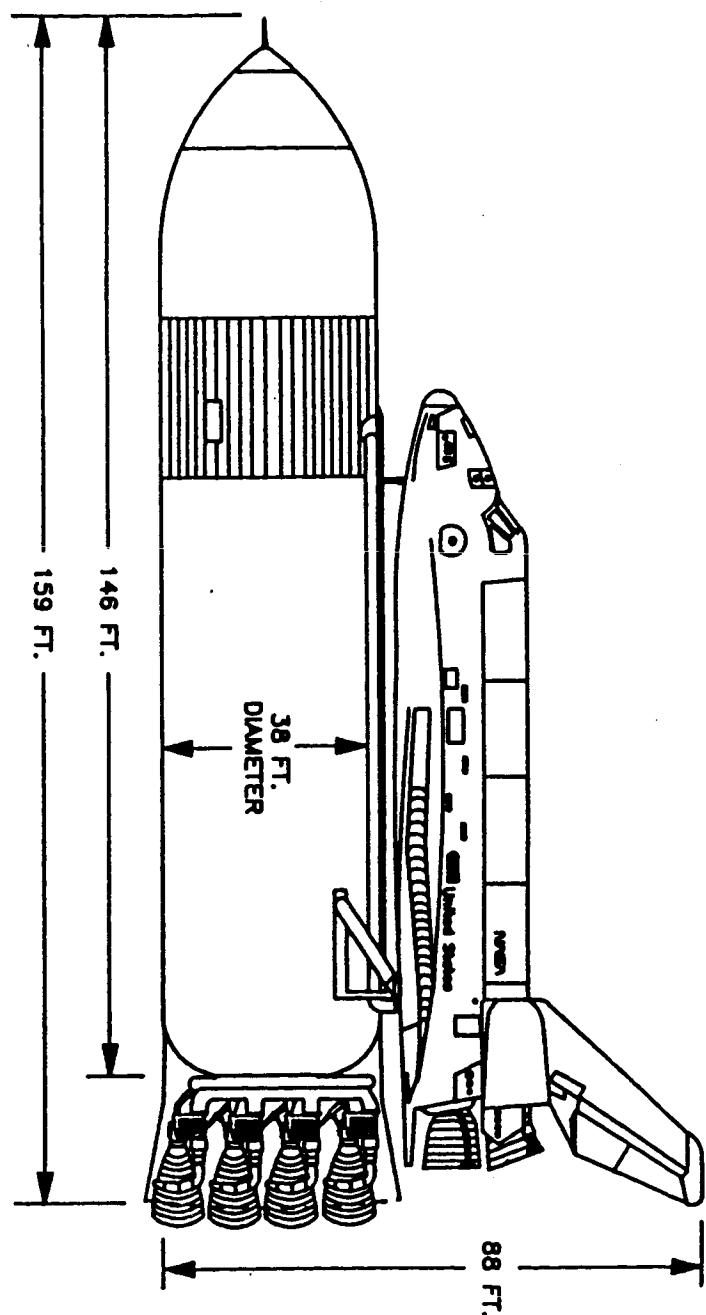
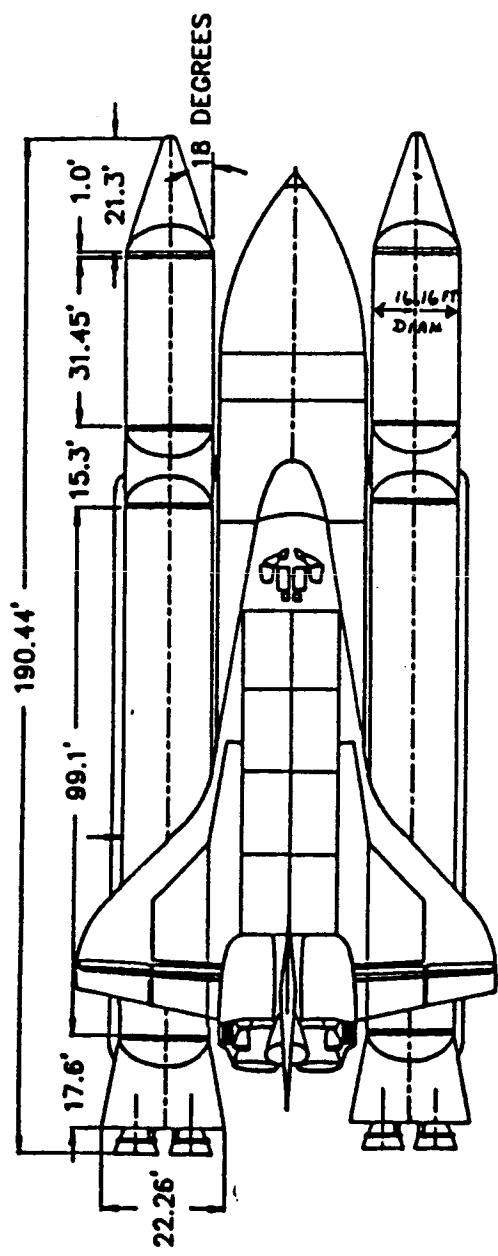
- 1) "Liquid Rocket Booster Study," General Dynamics Space Systems Division, NASA Marshall Space Flight Center, NAS8-37137, 18 MAY 1988
- 2) Douglas G. Thorpe, "Space Shuttle with Common Fuel Tank for Liquid Rocket booster and Main Engines (Supertanker Space Shuttle)" Space Transportation Propulsion Technology Symposium, June 1990
- 3) "Shuttle Systems Weight and Performance," NASA Lyndon B. Johnson Space Center, JSC-NSTS-09095-95, 17 October 1989

ATTACHMENT TO "DETERMINING CRITERIA FOR SINGLE SINGLE STAGE TO ORBIT"

	<u>LH2/LOX LRB</u>	<u>SUPERTANKER</u>	SINGLE STAGE TO-ORBIT
MECO CONDITIONS			
Time	497 seconds	485 seconds	344 seconds
Altitude	360,670 ft	360,670 Ft	360,670 Ft
Velocity	30,280 Ft/sec	30,280 Ft/sec	30,280 Ft/sec
Manned Orbiter Configuration			
MECO mass	357,700 lb	410,400 lb	N/A
Orbiter Inert	192,700 lb	192,700 lb	N/A
Orbiter Payload	81,400 lb	80,600 lb	N/A
Propellant Tank	66,800 lb	120,300 lb	N/A
Residual Propellant	1,500 lb	1,500 lb	N/A
OMS Propellant	15,300 lb	15,300 lb.	N/A
3-engine Shuttle-C Configuration			
MECO mass	357,700 lb	410,400 lb	398,000 lb
Payload Carrier	24,500 lb	24,500 lb	24,500 lb
Propulsion Boattail	55,200 lb	55,200 lb	55,200 lb
Avionics and Cont.	11,400 lb	11,400 lb	11,400 lb
Payload	183,000 lb	182,200 lb	32,400 lb
Booster Engines	N/A	N/A	54,500 lb
Booster Propulsion Mass	N/A	N/A	73,000 lb
Propellant Tank	66,800 lb	120,300 lb	120,300 lb
Residual Propellant	1,500 lb	1,500 lb	1,500 lb
OMS Propellant	15,300 lb	15,300 lb	15,300 lb
STAGING CONDITIONS			
Time	121.3 sec	138.3 sec	N/A
Altitude	136,200 Ft	163,000 Ft	N/A
Mach Number	4.666	5.6	N/A
Delta V	8,909 Ft/sec	10,900 Ft/sec	N/A
Mass After Staging	1,552,400 lb	1,552,400 lb	N/A
Booster Dry Mass(ea)	119,500 lb	127,500 lb	N/A
Ascent Propellnt(ea)	610,500 lb	2,158,000 lb	N/A
ET Ascent Propellant	391,500 lb	N/A	N/A
Booster Jettisoned Mass	502,500 lb	127,500 lb	N/A
3-engine Shuttle-C Configuration (additional)			
Jettisoned mass	11,900 lb	11,900 lb	11,900 lb
LIFT-OFF CONDITIONS			
Gross Lift-Off Weight	3,416,100 lb	3,838,000 lb	3,782,400 lb
Thrust	5,085,100 lb	5,085,000 lb	5,085,000 lb
Thrust-to-Weight	1.489	1.325	1.344

LO₂ / LH₂ LIQUID ROCKET BOOSTER

SUPER-TANKER



Eq 1) $V_b = G * \text{Ave Isp} * \ln(GLOW / M_{orb}) - k * G * t$

Eq 2) Average Vehicle Isp =

$$[(Isp_1 * Thrust_1) + (Isp_2 * Thrust_2)] / (Thrust_1 + Thrust_2)$$

Eq 3) Mass to Orbit = Fuel / $[(\exp(955 / Isp)) - 1]$

Eq 4) Gamma = (Non Payload / GLOW) * $\exp(955/Isp)$

STO is achievable if GAMMA is less than 1.0

HARDWARE COST COMPARISON

ET - SSME

*(6) \$45 million engines + \$30 million tank = \$300 million for 52,000 lbs payload
(\$5,769 / lb payload)*

ET - J2

*(12) \$10 million engines + \$30 million tank = \$150 million for 30,960 lbs payload
(\$4,839 / lb payload)*

ET - INTEGRATION PROPULSION MODULE

*(4) \$3 million engines +\$30 million tank = \$42 million for 31,000 lbs payload
(\$1,350 / lb payload)*

SINGLE STAGE TO ORBIT BENEFITS:

- *Extreme reduction in processing time
24 hours from Receiving to Launch*
- *Internationally competitive launch vehicle system*
- *Reduction in Vehicle Hardware, Systems, & Manpower*
- *Reduction in Launch Site supporting Infrastructure*
- *Extremely flexible to vehicle manifest*
- *Big return in Technology Investment*
- *Good morale from readily visible accomplishments*
- *All bets are off if OEPSS Technologies are not implemented*
 - Leakfree Joints*
 - Total Automated Checkout of vehicle*
 - Passive Payloads*
 - No Artificial Interfaces*
 - Vehicle Propulsion System is preconditioned*
 - Structural mating of Cargo Pod requires Passive Attachment*